FLOAT Project - Task 1

Preliminary Float Design and Economical Considerations

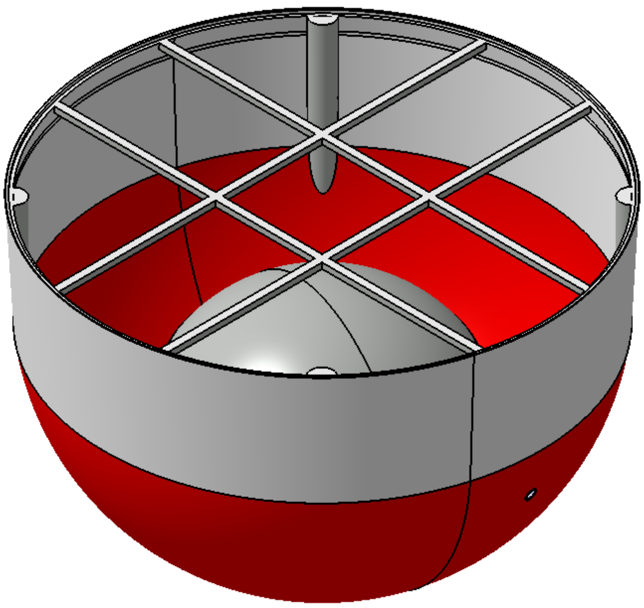
Marchalot, Tanguy; Kofoed, Jens Peter; Sørensen, Eigil V.; Hansen, S.M.G.; Frier, Christian

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

FLOAT Project – Task 1
Preliminary float design and economical considerations

T. Marchalot
J. P. Kofoed
E. V. Sørensen
S. M. G. Hansen
C. Frier



ISSN 1901-726X
DCE Technical Report No. 113

AALBORG UNIVERSITY
Department of Civil Engineering

Aalborg University
Department of Civil Engineering
Water and Soil

DCE Technical Report No. 113

FLOAT Project – Task 1
Preliminary float design and economical considerations

by

T. Marchalot
J. P. Kofoed
E. V. Sørensen
S. M. G. Hansen
C. Frier

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2011 by
Aalborg University
Department of Civil Engineering
Sohngaardsholmsvej 57,
DK-9000 Aalborg, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 113

Recent publications in the DCE Technical Report Series

Survivability Mode and Extreme Loads on the Mooring Lines of the Wave Dragon Wave Energy Converter. / Parmeggiani, Stefano ; Kofoed, Jens Peter.
Aalborg : Aalborg University. Department of Civil Engineering, 2011. 51 p. (DCE Technical Reports; 108).

Analyse af vindforhold på Viborgvej/Bredskiftevej. / Rasmussen, Michael R. ; Lauridsen, Thomas Bank ; Kjemtrup, Inge-Mette ; Hjul, Jonatan.
Aalborg : Institut for Byggeri og Anlæg, Aalborg Universitet, 2010. 39 p. (DCE Technical Report; 84)..

Analyse af vindklima ved Navitas Park. / Rasmussen, Michael R. ; Lauridsen, Thomas Bank.
Aalborg : Institut for Byggeri og Anlæg, Aalborg Universitet, 2010. 29 p. (DCE Technical Reports; 99).

Preface

The objective of the FLOAT project is to study the reliability of high-performance fibre-reinforced concrete, also known as Compact Reinforced Composite (CRC), for the floats of wave energy converters. In order to reach commercial breakthrough, wave energy converters need to achieve a lower price of energy produced, comparable to prices currently obtained from offshore wind power, and this can be done by the use of more suitable materials. The flotation device is a key part of converters, as it accounts for a considerable share of initial investment, up to 27% depending on the converter (dexawave.com, 2011). CRC floats could be a very cost-effective technology with enhanced loading capacity and environmental resistance, and very low maintenance requirements, affecting directly the final energy price. The project involves DEXA Wave Energy Ltd, Wave Star A/S, Aalborg University and Hi-Con A/S. It is divided in 4 tasks:

Task 1: Preliminary float design and economical considerations

Task 2: Material characteristics

Task 3: Preliminary experiences

Task 4: The importance for wave energy

The present report covers Task 1.

Contents

1. Introduction

The first task of the FLOAT project is a theoretical and numerical study including preliminary float designs and costs estimations. It aims at making a first comparison between the different materials options for DEXA and WaveStar floats and giving a first judgement about the suitability of CRC concrete.

To that end, some tables have been prepared compiling qualitative (ageing, repairability, environmental impact, etc.) and quantitative data (weight, cost, etc.) with a star-rating system for different materials options: steel, CRC concrete, ordinary concrete and glass-reinforced plastic. These tables permit to compare easily the pros and cons of each material.

Some calculations had already been done by the WaveStar Float Design Group to estimate the weights and costs of the WaveStar floats depending on the material chosen. For DEXA these estimations have been carried out by Christian Frier of Aalborg University and by Søren Mosegaard Goul Hansen of Hi-Con.

2. WaveStar

Some important design calculations had already been carried out by the WaveStar Float Design Group (WaveStar Float Design Group, 2011). They considered steel, CRC concrete and glass-reinforced plastic as different material options. For each of these materials, they estimated the weight of the float, the times of design, mould production and float production, the costs of tooling, production and transport and the environmental impact. All the figures of this study for WaveStar are taken from their report "Arm Float Bearing Table Overview".

Aalborg University tried to extend this comparison study to more general criteria (ageing, repairability, strength, etc.). The tables are given in [Annex 1 & 2].

We can deduct from this comparison study that **CRC concrete** can be an interesting option given its low production costs (70.000 kr./float). Another interesting point is its slow ageing in a marine environment. CRC concrete is subject to erosion, chemical action and eventual corrosion of the reinforcements but these phenomena occur at rates slower than the corrosion endured by the steel floats, and no maintenance operations are needed. CRC floats can also be produced relatively quickly (2 days/float), once the mould has been designed and produced (6 months). Lastly, it has considerable fatigue resistance.

The essential drawback of this material is its weight: 10.02 tons. It is a very important aspect for WaveStar structure, because the floats need to be lifted up in storm situation. The low production costs of the CRC floats are a bit offset by high tooling costs, but if we consider the production of 20 WaveStar machines (400 floats), the impact of these high tooling costs is considerably attenuated. Furthermore, CRC concrete is a new material and no published material data is available, therefore some prototypes need to be studied.

Ordinary concrete would also feature very low production costs, but the high weight of ordinary concrete floats is prohibitive for their use with the Wave Star machine.

Steel has the advantages of a very fast production (1 day/float) and that no mould is needed for the float production. Besides, it is a well-known material, so no testing of the steel floats is needed. Finally, steel presents a good repairability (it is easy to repair a damaged piece by welding or screwing) and important mechanical strength.

On the other hand, **steel** floats are heavy (12 tons), and of all the materials studied, it is the one with the worst long-term behaviour in a marine environment: it is prone to corrosion and fouling, so it needs maintenance operations every 10 years to redo the anti-corrosion and anti-fouling coatings. The impact of these coatings on marine life is regulated but still not well known. The environmental footprint involved by the steel float production is very important (426.000 MJ of primary energy and 33.000 kg of CO_2). Steel also presents a bad fatigue resistance.

The feature of **fibre glass composite** floats that makes it very competitive is its low weight: 1,5 tons. As explained before, it is very interesting in storm protecting situation when the floats need to be lifted up. It shows good mechanical properties (high strength and fatigue resistance), and it can be repaired by applying new layers of fibre glass, but the very specific working conditions make it difficult.

However, **glass-reinforced plastic** compensate its good mechanical properties and low weight by high construction costs (310.000-460.000 kr./float). It is corrosion-resistant but it suffers damage due to water intake (hydrolysis), degradation from UV radiation and fouling. Consequently, some maintenance operations have to be carried out once a year. Another drawback of this option is its production time: the production of a composite float lasts 1 week.

3. DEXA

The task 1 of the FLOAT project regarding DEXA involved more calculations because fewer efforts had been put into preliminary designs than for WaveStar.

The main difference between the two energy converters is that contrary to WaveStar, the weight of DEXA floats is not crucial: the floats are always submerged and don't need to be lifted up. Consequently, the use of concrete, whose weight was a problem for WaveStar, is particularly interesting in this application and can lead to important cost reductions. Glass-reinforced plastic floats, whose essential feature is its low weight, and steel, which brings problems of ageing and maintenance, won't be studied here.

Therefore, two preliminary designs will be carried out: one in ordinary concrete and one in CRC, and this task will essentially consist in comparing these two materials.

Christian Frier of Aalborg University designed the concrete float [Annex 5] and Søren Mosegaard Goul Hansen of Hi-Con designed the CRC float [Annex 6]. In order to make this design, an extreme loading situation has been estimated by Tanguy Marchalot of Aalborg University [Annex 4].

The conclusion of this study is that CRC may not be very suitable for DEXA floats compared to ordinary concrete. On one hand, the use of CRC offers a little weight gain (15,2 tons instead of 16,3 tons for ordinary concrete), but this is not essential in this application as above-said.

Choosing CRC would imply higher costs (50 k€ against 10 k€ for an ordinary concrete float) and higher carbon footprint than ordinary concrete (120.000 MJ of primary energy and 7.000 kg of CO_2 involved in the CRC "cradle to gate" process against 35.000 MJ and 4.000 kg for the ordinary concrete), making ordinary concrete probably more adapted to this application.

4. Conclusion

The improved properties of CRC combined with its low construction costs make it a very interesting material for wave energy applications.

First, its very low porosity and its resistance to corrosion provide it an increased durability, which is a critical aspect in a marine environment. It does not need any coating, making the maintenance needing nonexistent, another very important feature in offshore applications, where all maintenance operations are extremely expensive.

CRC features enhanced mechanical properties that can lead to lower weight, often a determinant aspect in offshore designs. It also offers the good fatigue resistance necessary for a structure subject to wave-induced repetitive loadings.

Finally, despite high tooling costs, the very low production costs of CRC floats compared to steel or glass-reinforced plastic make it an option that cannot be ignored.

For wave energy converters for which the floats weight is not very important factor such as DEXA, ordinary concrete, which also offers good durability and good mechanical properties for lower costs than CRC, might be the most suitable option. But for WaveStar for instance, the crucial lower weight offered by the use of CRC combined with its improved durability and its low cost make indicates it probably is a very suitable option.

It is concluded, from the WaveStar example, that the use of CRC for floats of wave energy converters is an option that can lead to important cost savings, given its good mechanical properties, long durability and low production costs.

Annexes

Annex 1. General criteria

	STEEL	GRP	CRC	Concrete
Marine environment impact (1)	★ Toxic coatings	★★	★★★	★★★
Corrosion resistance	★	★★★	★★★	★★★
Environmental ageing (2)	★ Corrosion	★★ Damage on plastic due to water intake (hydrolysis), degradation from UV radiation	★★★ Erosion, chemical action (very low rates)	★★ Erosion, leaching, corrosion of reinforcement
Repairability (3)	★★ Welding/screwing	★ Applying new layers of glass fibers	★★ Mounting a mould on the float	★★ Mounting a mould on the float
Strength	★★★	★★	★★	★
Maintenance	★★ /10 years	★ /year	★★★ None	★★★ None
Fatigue resistance	★	★★★	★★★	★★
Residual life after service life (4)	★	★★	★★★	★★★
Working environment (5)	★★	★	★★★	★★★

(1) The marine environment impact refers to the influence that the floats can have on the surrounding sea life. The impact of anti-corrosion and anti-fouling coatings necessary for steel and glass-reinforced plastic isn't well known, making it a drawback compared to the concrete options that don't need any coatings.

(2) The floats are prone to very different ways of ageing depending on the material used. The material the most attacked by a marine environment is steel, which suffers important corrosion. CRC concrete, given its low porosity, is less subject to erosion and leaching, leading to low rates of marine growth, because of the little number of asperity to develops marine life.

(3) The repairability is the easiness with which some repairing can be done on the floats in case of small damage (due to a floating object impact, for instance). For WaveStar, this repairing can be done in situ by lifting the floats out of the water, but for DEXA, the whole structure has to be taken out of the sea. The low mark of glass-reinforced plastic is here due to the necessity of very specific working conditions to manipulate it.

(4) Almost any service life can be achieved by an adapted design. But this refers to the life that can be expected once the service life has been reached. Concrete has been proved to have very low ageing rates: a concrete ship from WWI is still afloat as part of a breakwater with other WW2 concrete ships for a pulp and paper mill in Powell River in British Columbia, Canada, and still in an surprisingly good condition. (Concrete Ships.org)

(5) Investigations suggest an increased risk for workers in glass-reinforced plastic manufacture to develop health problems: skin problems due to exposition to various chemical agents, glass fibre and dust including shortened glass fibre and plastic particles (MINAMOTO, et al., 2002), but also irritation and effects on the central and peripheral nervous system due to exposition to styrene (VAN ROOIJ, 2008).
Regarding steel manufacturing, dust and fume may be generated during processing e.g. in welding, cutting and grinding. If airborne concentrations of dust and fume are excessive, inhalation over long periods may affect workers' health, primarily of the lungs (Fagersta Stainless, 2007).

Annex 2. Specific criteria for WaveStar

	STEEL		GRP		CRC		Concrete	
Production cost per float for 20 floats with fixed costs	NA		★ 310.000-460.000 kr.		★★ 70.000 kr.		★★★	
Tooling costs per float **For 20 floats** **For 20 machines**	NA		★★ ≈400.000/20=20.000 kr. ≈400.000/400=1.000 kr.		★ ≈2.000.000/20=100.000 kr. ≈2.000.000/400=5.000 kr.		★	
Weight	★ 12 tons		★★★ 1,5 ton		★ 10,02 tons		★	
Carbon footprint (1) **Primary Energy** **CO_2**	★ 426.000 MJ 33.000 kg		★★ 150.000 MJ 11.500 kg		★★★ 79.000 MJ 4.600 kg		★★★	
Float design time	★ 6 months		★★★ 3 months		★★★ 3 months		★★★	
Mould production & design time	★★★ None		★★ 3 months		★ 6 months		★	
Float production time (2)	★★★ 1 day		★ 1 week		★★ 2 days		★★	
Surface treatment against marine growth (3)	Yes		Yes		No		No	
Testing	No		No		Prototype needed			
Summary	**Pros**	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
	Fast production No mould Known material Easy repair	Heavy Corrosion Toxic coatings	Light Good fatigue	Slow production Expensive	Cheap Fast production	Untried material High tooling costs	Cheap Fast production	Heavy

(1) This carbon footprint only considers the environmental impact due to the fabrication of the float ("cradle to gate"), not the whole life cycle impact.
(2) This float production time doesn't include times of coating applications and surface treatments.

(3) Marine growth is particularly critical for WaveStar floats. Indeed, it can lead to important weight increase, making the lifting difficult in storm conditions. Steel and GRP require the application of anti-fouling coatings, contrary to concretes. It can be noted that due to the lower erosion and leaching rates of CRC concrete, the marine life would also grow at a lower rate, due to the fewer asperities.

Annex 3. Specific criteria for DEXA

<table>
<tr><th></th><th colspan="2">STEEL</th><th colspan="2">GRP</th><th colspan="2">CRC</th><th colspan="2">CONCRETE</th></tr>
<tr><td>Production cost per float for a 50 unit park (1)</td><td colspan="2">★★★</td><td colspan="2">★</td><td colspan="2">★★
50.000 €</td><td colspan="2">★★★
10.000 €</td></tr>
<tr><td>Tooling costs</td><td colspan="2"></td><td colspan="2">★★</td><td colspan="2">★</td><td colspan="2">★</td></tr>
<tr><td>Weight</td><td colspan="2">★</td><td colspan="2">★★★</td><td colspan="2">★
15,2 tons</td><td colspan="2">★
16,3 tons</td></tr>
<tr><td>Carbon footprint (2)
Primary Energy
CO_2</td><td colspan="2">★</td><td colspan="2">★★</td><td colspan="2">★★
120.000 MJ
7.000 kg</td><td colspan="2">★★★
35.000 MJ
4.000 kg</td></tr>
<tr><td>Float design time</td><td colspan="2">★</td><td colspan="2">★★★</td><td colspan="2">★★★</td><td colspan="2">★★★</td></tr>
<tr><td>Mould production & design time</td><td colspan="2">★★★
None</td><td colspan="2">★★</td><td colspan="2">★</td><td colspan="2">★</td></tr>
<tr><td>Float production time</td><td colspan="2">★★★</td><td colspan="2">★</td><td colspan="2">★★</td><td colspan="2">★★</td></tr>
<tr><td>Need of testing</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">Prototype needed</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Summary</td><td>Pros</td><td>Cons</td><td>Pros</td><td>Cons</td><td>Pros</td><td>Cons</td><td>Pros</td><td>Cons</td></tr>
<tr><td>No mould
Fast production
Known material
Easy repair</td><td>Heavy
Corrosion
Toxic coatings</td><td>Light
Good fatigue</td><td>Slow production
Expensive</td><td>Cheap
Fast production</td><td>Untried material
High tooling costs</td><td>Cheap
Fast production</td><td>Heavy</td></tr>
</table>

(1) This cost estimation is taken from DEXA Cost of Energy Assessment.

(2) This carbon footprint estimation considers the same ratios Primary Energy/Weight and CO_2/Weight as the ones used for WaveStar floats.

Annex 4. DEXA – Load Estimations

1. Wave conditions

In order to estimate the loads on the floats, we need a design wave condition representative of Hanstholm climate. The characteristics of the extreme conditions are referenced in the table below:

Average energy flux [kW/m]	Distance from coast [km]	Water depth [m]	Hm0 10 years design [m]	Tp 10 years design [s]	Hm0 50 years design [m]	T_p 50 years design [s]	H_{m0} 100 years design [m]	T_p 100 years design [s]
12	100	31	7.5	11.4	8.4	12.1	8.7	12.3

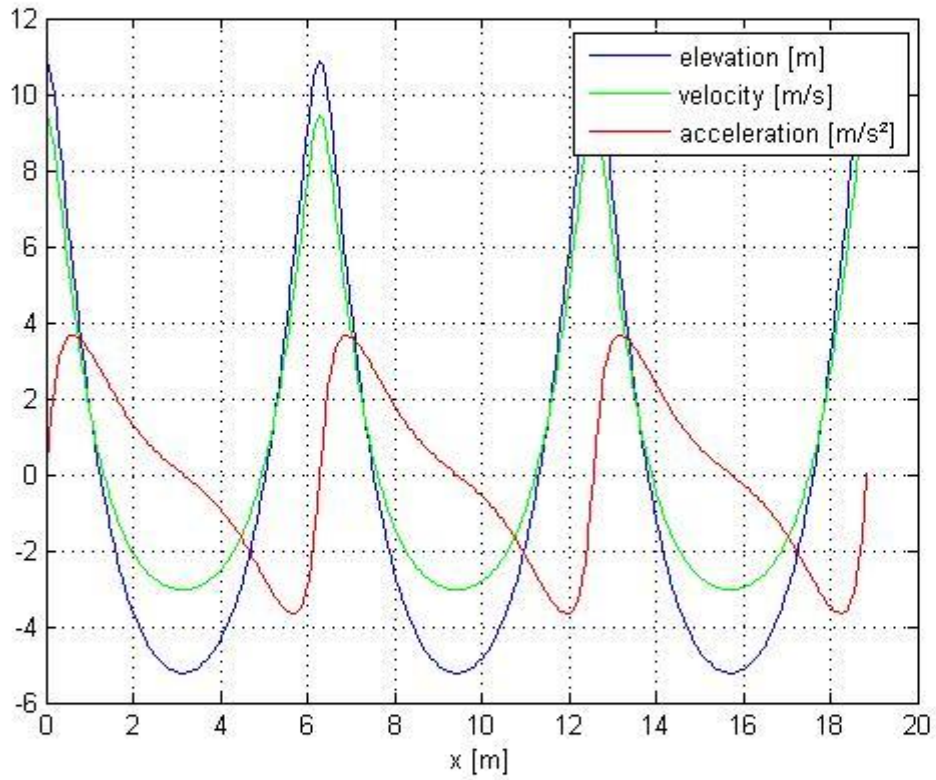
The loads on the structure due to wave action are calculated for H_{max} corresponding to 50 and 100 years events. H_{max} is here set as the largest of 1000 waves in the extreme wave states, leading to H_{max} = 1,85 H_s, assuming Rayleigh distribution of the wave heights.

To investigate the influence of the wave periods, different periods have been chosen in an interval around the peak period (according to DS 449).

Hmax [m]	T [s]
15,5	10,4
	12,7
	14,9
16,1	10,6
	12,9
	15,1

2. Wave profile

For each wave situation, the horizontal particle velocities and accelerations in the wave are calculated. Here is the wave profile calculated with the Stream Function Theory for the [H_{max}=16,1m ; T=10,6s] situation, the wave state that shows the highest particle velocities and accelerations:



Wave profile for [Hmax=16,1m ; T=10,6s]

3. Force estimation – the Morison's equation

Then we can estimate the force applied on the float with Morison's equation, considering the float fixed, that is to say at the end position of the mooring system. It is the sum of an inertia force and a drag force:

$$f_N(t) = \rho(1+C_A)A\dot{v} + \frac{1}{2}\rho C_D D v|v|$$

Where ρ is the density of the water = 1025 [kg/m^3]

C_A the added mass coefficient = 1 [-]

A the cross-sectional area = πD²/4 [m²]

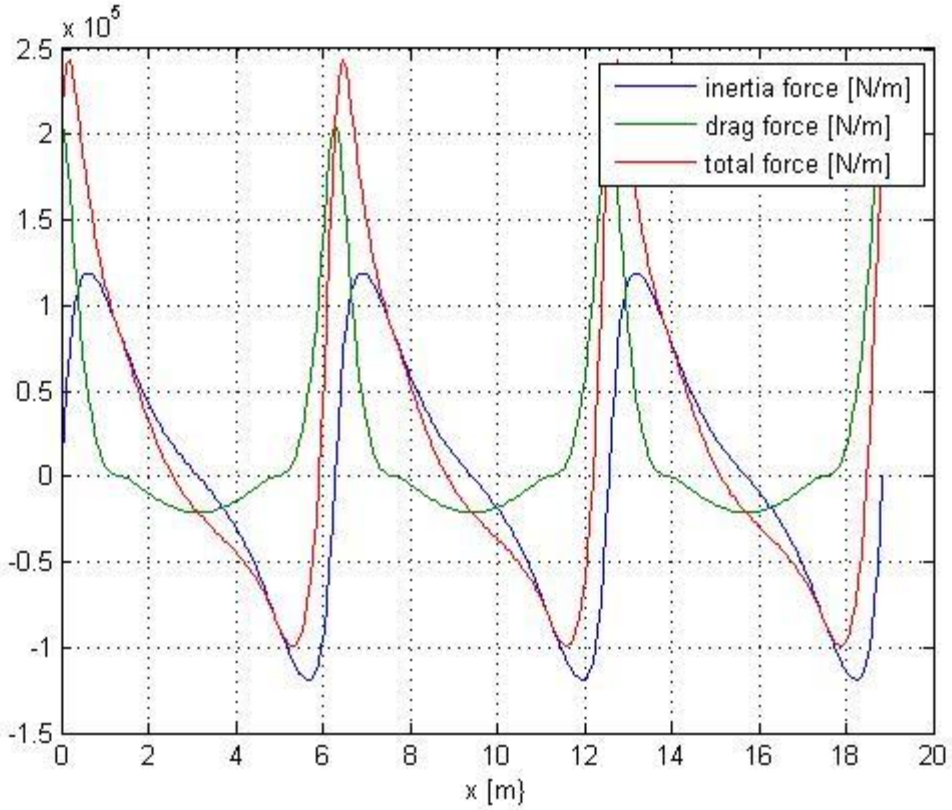
D the diameter of the float = 4,5 [m]

v the horizontal particle velocity [m/s]

$\dot{v}$ the horizontal particle acceleration [m/s²]

C_D the drag coefficient = 1 [-]

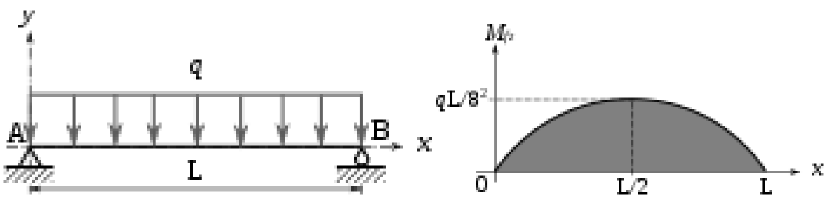
Here is the force profile found for the [Hmax=16,1m ; T=10,6s] situation:



Force profile for [Hmax=16,1m ; T=10,6s]

4. Bending moment

We can now calculate the maximal bending moment in the middle of the float. We consider that the situation is equivalent to a simple beam under an evenly distributed load, with the two supports A and B corresponding to the steel support of the float, situated 2 meters from the end of the float, giving L=20m.



The maximal bending moment is estimated by:

$$M = \frac{qL^2}{8}$$

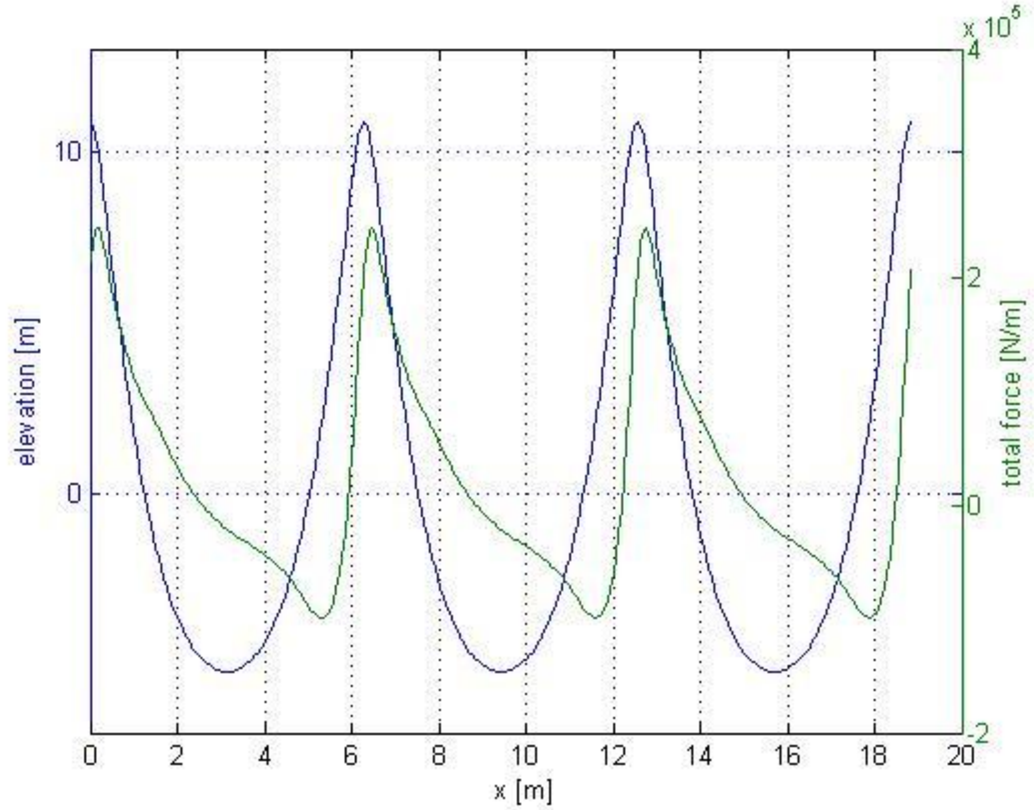
With q the maximal force applied to the float.

5. Results

Results are summarized in the following table:

Hmax [m]	T [s]	v [m/s]	a [m/s²]	F [MN/m]	M [MN.m]
15,5	10,4	8,9	3,5	0,22	11,1
	12,7	8,1	3,0	0,18	9,1
	14,9	7,9	2,8	0,17	8,6
16,1	**10,6**	**9,5**	**3,6**	**0,24**	**12,2**
	12,9	8,6	3,2	0,20	10,1
	15,1	8,4	2,9	0,19	9,5

We obtain a maximal bending moment of 12,2 MN.m, for the wave situation (H_{max}=16,1m ; T=10,6s). These results are characteristic values, and a security coefficient must be applied for the structure design.



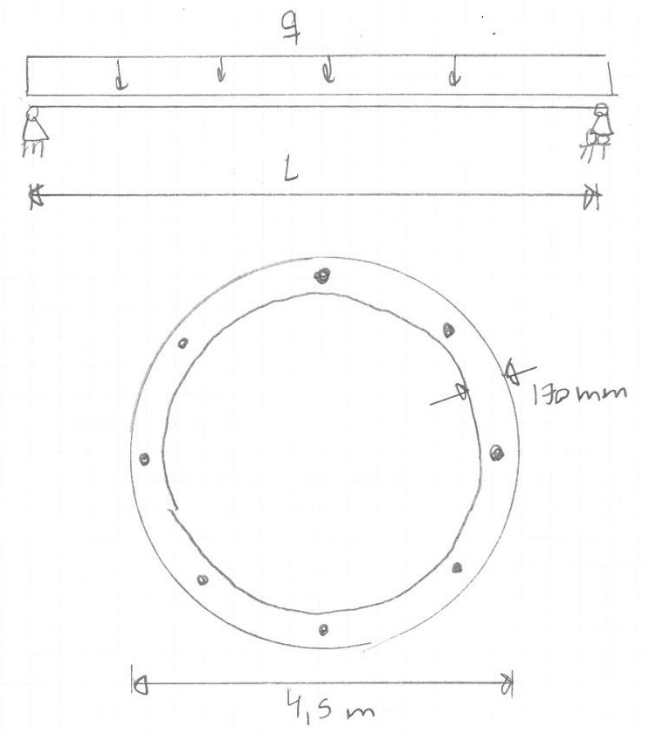
Total force and elevation for [Hmax=16,1m ; T=10,6s]

Annex 5. Dexawave Design, conventional pre-stressed concrete

A concrete tube with length L = 20 m and outer diameter D = 4.5 m is considered. The characteristic compressive strength of the concrete is f_{ck} = 40 MPa. The partial safety factor for the compressive strength is assumed to be 1.45 and the failure strain ε_{cu} = 0.0035. The load from the waves is applied as an evenly distributed load of q = 0.5 MN/m along the tube. By assuming that the tube is a simply supported beam, the maximum moment in the middle of the span becomes:

$$M_{\max} = \frac{1}{8} q L^2 = \frac{1}{8} 0.5 \cdot 20^2 = 25 \quad \text{MN/m}$$

The thickness of the tube is set to 170 mm, allowing a cover thickness for the concrete of 70 mm on each side of the reinforcement situated in the center of the tube section. Thus the inner diameter of the tube is d = 4.16 m.



Pre-stressing force

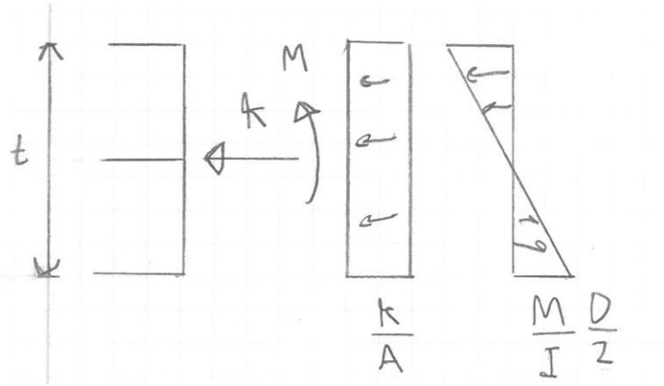
The concrete material is considered to be linear elastic when determining the necessary pre-stress for avoiding tensile normal stresses in the direction of the tube. Sectional properties, A and I, for the tube become:

$$A = \frac{\pi}{4}\left(D^2 - d^2\right) = \frac{\pi}{4}\left(4.5^2 - 4.16^2\right) = 2.31 \quad \text{m}^2$$

$$I = \frac{\pi}{64}\left(D^4 - d^4\right) = \frac{\pi}{64}\left(4.5^4 - 4.16^4\right) = 5.43 \quad \text{m}^4$$

The maximum tensile stress with pre-stress force, *K*, becomes:

$$\sigma_t = \frac{K}{A} - \frac{M_{\max}}{I}\frac{D}{2}$$



By demanding that $\sigma_t \geq 0$ the required pre-stress force is obtained:

$$K \geq A\frac{M_{\max}}{I}\frac{D}{2} = 2.31\frac{25}{5.43}\frac{4.5}{2} = 23.96 \quad \mathrm{MN}$$

By assuming a pre-stressing force of 25 MN, the following minimal and maximal stresses are obtained:

$$\sigma_t = \frac{K}{A} - \frac{M_{\max}}{I}\frac{D}{2} = \frac{25}{2.31} - \frac{25}{5.43}\frac{4.5}{2} = 0.45 \quad MPa$$

$$\sigma_c = \frac{K}{A} + \frac{M_{\max}}{I}\frac{D}{2} = \frac{25}{2.31} + \frac{25}{5.43}\frac{4.5}{2} = 21.18 \quad MPa$$

The maximum compressive force in the pre-stressed section should not exceed 0.55 f_{ck} according to [1]. Thus:

$$\sigma_c = 21.18 \quad MPa \quad \leq \quad 0.55 \cdot f_{ck} = 0.55 \cdot 40 = 22 \quad MPa$$

The criterion is just fulfilled.

Pre-stressing reinforcement

By using pre-stress wires with a diameter of 15.7 mm and a maximum tensile stress of 1860 MPa from Skandinavisk spændbeton, a maximum tensile force of 221 kN for each wire can be applied. In order not to load the wires too much, each line is stressed to 200 kN. The number of required wires is then:

$$n = \frac{K}{K_{line}} = \frac{25{,}000}{200} = 125$$

The wires are supposed to be positioned in 8 channels situated evenly around the diameter of the tube, thus the number of wires within each channel is 15.63. Then 16 wires adding to a total of 128 are selected which are to be pre-stressed to:

$$K_{line} = \frac{K}{n} = \frac{25{,}000}{128} = 195.31 \quad \text{kN}$$

Buckling

The tube can be considered as a simply supported reinforced column, and thus, there is a risk of global buckling. According to [2], buckling is not an issue, when the relative slenderness factor fulfills $\lambda \leq \lambda_{lim}$:

$$i = \sqrt{\frac{I}{A}} = \sqrt{\frac{5.43}{2.31}} = 1.53 \quad \text{m}$$

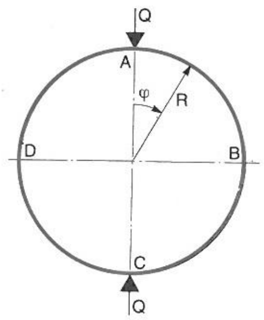
$$\lambda = \frac{L_s}{i} = \frac{20}{1.53} = 13.07$$

$$\lambda_{\lim} = 20\sqrt{\frac{A\, f_{cd}}{K}} = 20\sqrt{\frac{2.31 \cdot 40/1.45}{25}} = 31.93$$

Global buckling of the tube is not an issue.

Compression of cross-section

A simple analysis is performed to check if the cross-section can resist to be compressed when the load q is acting on the tube from one side and the tube is supported from the other side. The following static system from [3] is regarded to give a solution on the safe side. The tube is modeled as a circular beam loaded with a force Q acting from each side. This is believed to give a higher moment within the beam, as if an evenly pressure is added. A unit length of the tube is considered, then Q = q = 0.5 MN/m.



The tube is assumed to be reinforced with 3 ø12 rebars around the circular section pr m. The rebars are assumed to be situated in the middle of the cross section of the beam. The characteristic yield stress of the steel is f_{yk} = 550 MPa, the modulus of elasticity E = $2 \cdot 10^5$ MPa and the partial safety factor is 1.2.

The radius of the beam is:

$$R=\frac{1}{2}\left(\frac{D}{2}+\frac{d}{2}\right)=\frac{1}{2}\left(\frac{4.5}{2}+\frac{4.16}{2}\right)=2.16 \quad \mathrm{m}$$

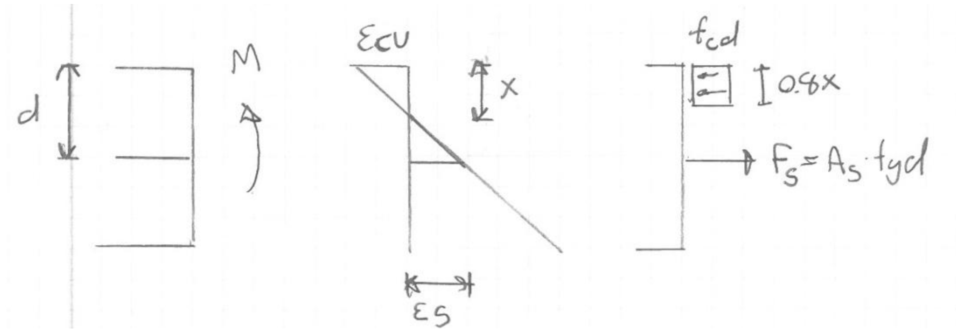
The moment within the beam can according to [3] be calculated to:

$$M(\varphi)=QR\left(\frac{1}{\pi}-\frac{1}{2}\sin(\varphi)\right)$$

The moment is changing sign with the angle φ, but as the reinforcement is positioned in the center of the cross-section only the maximum absolute moment is considered for design. This is obtained for $\phi = 0$

$$M_{\max}=M(0)=QR\frac{1}{\pi}=0.5\cdot 2.16\frac{1}{\pi}=0.34 \quad \mathrm{MNm/m}$$

The moment capacity of the cross-section can be calculated assuming that the cross-section is normal reinforced, thus the tensile strain within the reinforcement exceeds the yield strain, according to [2]. The computation assumes that compressive failure occurs in the concrete as the reinforcement is yielding corresponding to the strain/stress-distributions and moment shown in the figure:



The beam cross-section is rectangular with width *b* = 1000 mm and height *t* = 170 mm.

The reinforcement area:

$$A_s=3\cdot\frac{\pi}{4}12^2=339 \quad \mathrm{mm}^2$$

Cross -section effective height:

$$d=\frac{t}{2}=\frac{170}{2}=85 \quad \mathrm{mm}$$

Reinforcement ratio:

$$\omega=\frac{A_s\, f_{yd}}{b\, d\, f_{cd}}=\frac{339\cdot 550/1.2}{1000\cdot 85\cdot 40/1.45}=0.066$$

Yield strain of steel:

$$\varepsilon_y = \frac{f_{yd}}{E_s} = \frac{550/1.2}{2\cdot 10^5} = 0.0023$$

Reinforcement ratio corresponding to yield limit for steel:

$$\omega_{bal} = 0.8\frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_y} = 0.8\frac{0.0035}{0.0035+0.0023} = 0.48$$

As $\omega \le \omega_{bal}$ the cross section is normal reinforced as assumed. The neutral axis is positioned at a distance *x* from the top of the cross section:

$$x = \frac{1}{0.8}\omega d = \frac{1}{0.8}0.066\cdot 85 = 7.0 \quad \text{mm}$$

The strain in the reinforcement becomes:

$$\varepsilon_s = \varepsilon_{cu}\frac{d-x}{x} = 0.0035\frac{85-7.0}{7.0} = 0.0387$$

Thus, the strain in the rebars is well below the failure strain (ca. 0.1)

The moment capacity can then be obtained as:

$$M_{Rd} = \left(1-\frac{1}{2}\omega\right)\omega b d^2 f_{cd} = \left(1-\frac{1}{2}0.066\right)0.066\cdot 1000\cdot 85^2\cdot 40/1.45 = 12.78 \quad \text{MNm/m}$$

The moment capacity is much higher than the maximum moment of 0.34 MNm/m.

Conclusion

All in all it can be concluded that the concrete tube can resist the externally applied force of 0.5 MN/m when reinforced with 128 pre-stressed wires each with a diameter of 15.7 mm distributed with 16 wires in eight channels around the tube. Perpendicular to this, a reinforcement arrangement of 3 ø12 rebars each meter will resist compressing the tube cross section. However, a more detailed calculation of the moment capacity of the tube cross section is still to be carried out, assuming a plastic distribution of stresses.

References

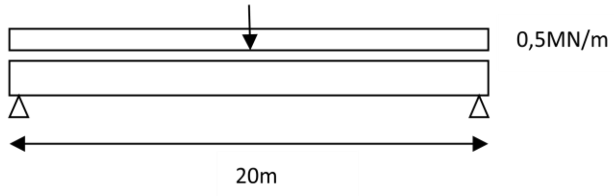
[1] : Søren Klock, noter vedr. spændbeton, Aalborg Universitet, Instituttet for Bygningsteknik, Oktober 2002.

[2]: Bjarne Chr. Jensen, Beton-konstruktioner efter DS/EN 1992-1-1, Nyt Teknik Forlag, 1. udgave 2008, ISBN 978-87-571-2668-6.

[3] : Bjarne Chr. Jensen, Teknisk Ståbi, Nyt Teknisk Forlag, 21. udgave 2011, ISBN: 978-87-571-2729-4.

Annex 6. Dexawave Design, CRC concrete

Det blev besluttet at anvende en model med en simpelt understøttet bjælke i form af en cirkulær beton-ring med en spændvidde på 20m og en diameter på 4,5m. Lasten fra bølgerne blev foreslået som en linjelast på 0,5MN/m.



Dette giver følgende moment:

M_d = 1/8 · 0,5MN/m · (20m)^2 = 25MNm

Ud fra flere overvejelser og undersøgelser vedrørende godstykkelsen af røret er det valgt, at den optimale tykkelse for et design med CRC-beton er på 150mm. Det giver et rør på 20m i længden, en ydre diameter på 4,5m og en indre diameter på 4,2m, hvilket giver godstykkelsen på 150mm.

Dette rør har følgende modstandsmoment:

W_x = π/32 · ((4,5m)^4 – (4,2m)^4)/4,5m = 2,16m^3

Trækspændingen i bunden af røret bliver da:

σ_s = 25MNm/2,16m^3 = 11,6 MPa

Røret er tænkt produceret i segmenter der senere efterspændes sammen og det er derfor nødvendig at opspænde tværsnittet til en større spænding en den trækspænding der vil forkomme. Det vurderes at en opspænding med 15MPa over hele tværsnittet bør være tilstrækkelig.

Tværsnitsarealet for røret er:

A_{150} = π/4 · ((4,5m)^2 – (4,2m)^2) = 2,05m^2

Den samlede efterspændingskraft:

F_e = 15MPa · 2,05m^2 = 31MN

Der efterspændes med Ø15,3mm liner, der har en regningsmæssig opspændingsspænding på 1100MPa. Hver line kan opspændes med følgende kraft:

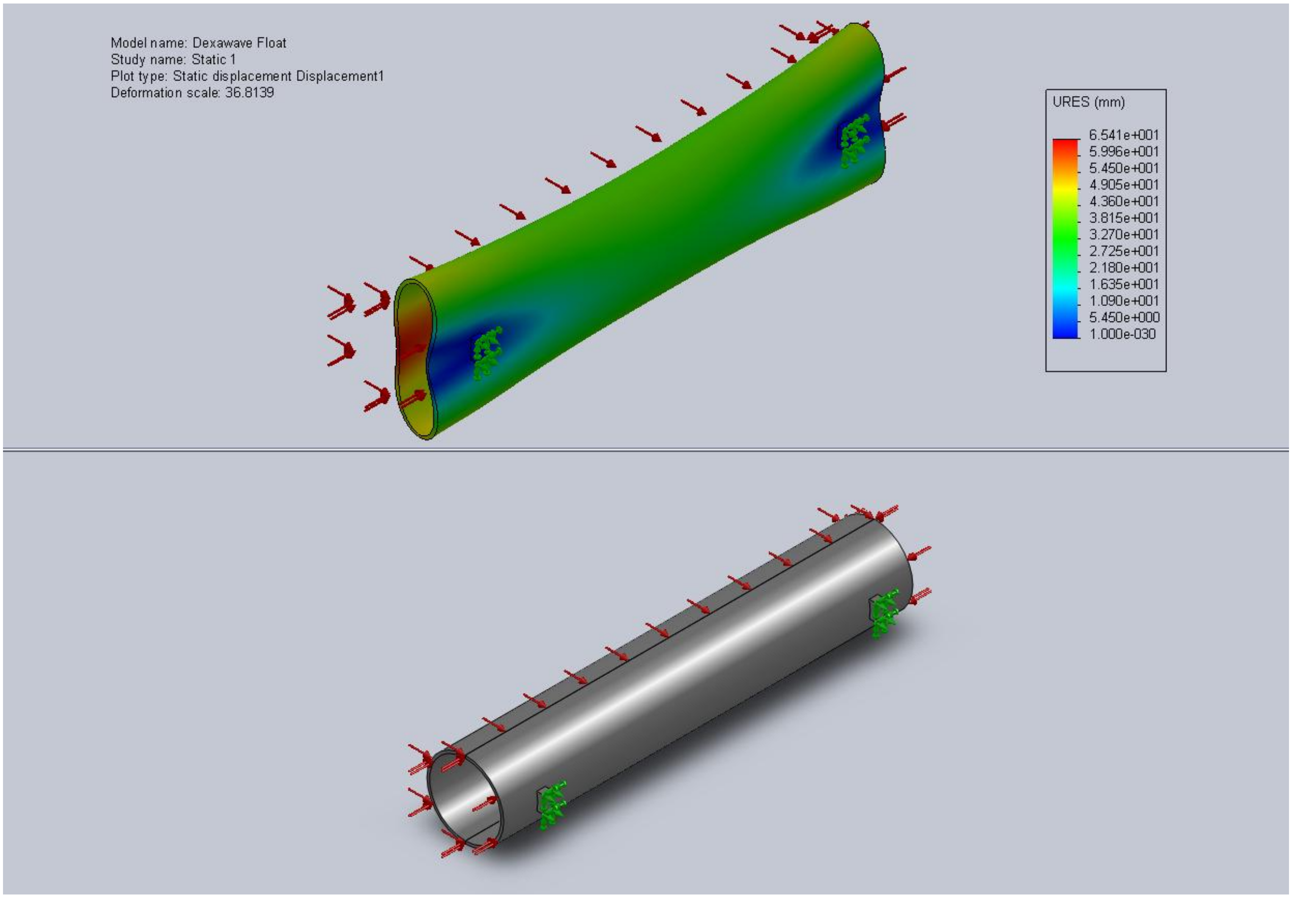
F_{op} = 1100MPa · (15,3mm/2)^2 · π = 202kN

Der skal anvendes følgende antal liner for at opspænde hele tværsnittet til 15MPa:

Antal liner = 31MN/202kN = 153,5 => min. 154 liner

Der opspændes med 160 liner fordelt med 20 liner i 8 stk Ø75 gennemgående udsparinger i tværsnittet. Linerne låses i låget, hvilket giver en jævn fordeling af opspændingen over hele tværsnittet i røret.

For at undersøge spændingsfordelingen i mere detaljeret for er der modeleret en FEM-model af CRC-røret, hvor der er påsat et tryk på 15MPa i begge ender af røret. Røret har som før en godstykkelse på 150 mm og en ydre diameter på 4,5m. Lasten er påsat som en jævnt fordelt tryk på 0,071MPa, hvilket svarer til en linjelast på 0,5MN/m.



Det ses af deformationsfiguren, at der vil opstå trækspændinger i rørets plan, hvilket også ses på figuren med von Mises spændingerne. Dette er specielt udtalt ved understøtningerne, hvor de største spændinger også ses.

For at optage disse trækspændinger på ca. 100MPa, skal der anvendes ringbøjler i elementerne. Der er ikke fortaget en detaljeret undersøgelse af, hvor mange og dimension af disse.

References

Concrete Ships.org. (n.d.). Retrieved from http://www.concreteships.org/ships/powellriver/

dexawave.com. (2011).

Fagersta Stainless. (2007). *Material Safety Data Sheet for Stainless Steel.*

MINAMOTO, K., NAGANO, M., INAOKA, T., KITANO, T., USHIJIMA, K., FUKUDA, Y., et al. (2002). Skin Problems among Fiber-Glass Reinforced Plastics. *Industrial Health* .

VAN ROOIJ, J. G. (2008). Trends in Occupational Exposure to Styrene in the. *The Annals of Occupational Hygiene* .

WaveStar Float Design Group. (2011). Table Overview - Arm Float & Bearing.